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Arctic Ship Design Impacts: Green Arctic Patrol Vessel (GAPV) Project

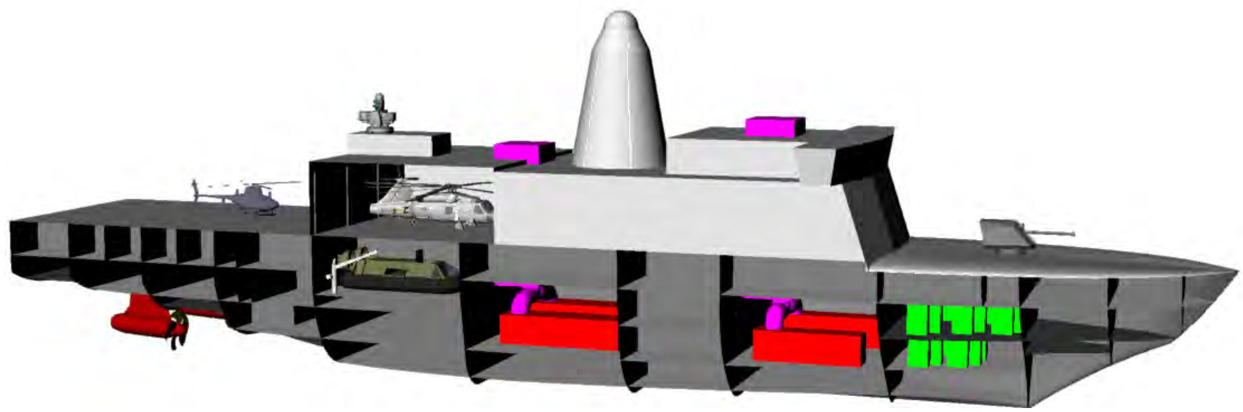

FIGURE 1 GAPV Internal View

ABSTRACT

Arctic warming and the resulting polar ice break up, is expected to increase traffic through the Arctic region for tourism, research, resource extraction, and transportation purposes. Understanding the US will have a strategic objective in the region in the coming decades, the current US Navy (USN) fleet is not designed to meet the challenges of operating in an Arctic environment. Anticipating that need, the Green Arctic Patrol Vessel (GAPV) project was started as a summer intern project in the Center for Innovation in Ship Design (CISD) at Naval Surface Warfare Center Carderock Division (NSWCCD) during the summer of 2009, and has completed its third iteration. The project developed a concept of operations and notional design for a USN Arctic Patrol Vessel capable of meeting current gaps in Arctic operational capability. The goal of this paper is to describe this vessel's design and highlight many of the high level impacts the Arctic environment has and will have on surface combatant design.

INTRODUCTION

Scientific forecasts indicate warming of the Arctic climate at twice the rate of the rest of the world. The resulting ice pack reduction will permit access to natural resource reserves, representing important financial opportunities for Arctic nations and adding significance to currently undefined territories. Shipping in and out of the Arctic for tourism, local needs and transport of natural resources to market continues to increase. While approximately 4.5 % of the world fleet is designed and built for polar use, a number expected to increase to 10%, a much smaller portion of USN and US Coast Guard (USCG) vessels are capable of polar operations. (Treadwell 2008)

In the USN, the 2030 surface fleet is expected to closely resemble the 2010 fleet, with the exception of more Littoral Combat Ships and no Frigates. The current fleet was not designed with arctic-operation in mind and new designs for the 2030 fleet do not currently consider this a requirement.

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The USN and USCG have recently published Arctic operational strategies to reflect requirements for a US maritime surface and air presence in the Arctic as climatic, economic and political changes occur. (USCG 2011) National policy has directed the development of capabilities and capacity to protect US borders; increase Arctic maritime domain awareness (MDA); preserve global mobility; project a sovereign United States maritime presence; encourage peaceful resolution of disputes; cooperate with other Arctic nations to address likely issues from increased shipping; establish a risk-based capability to address hazards in the region including cooperative Search and Rescue (SAR) sea basing and logistical support; and [use] the Arctic for strategic sealift. The most critical deficiencies identified by the USN include provision of environmental information, safe maneuvering on the sea surface and the conduct of training, exercise and education in the Arctic.

The GAPV design pictured in FIGURE 1 seeks to fulfill, in part, these stated defense needs while meeting environmental impact goals using current projections for the 2030 physical, political and economic landscape as a design basis. Comparable foreign designs, such as the Canadian Arctic/Offshore Patrol Ship (AOPS) and Norwegian *KV Svalbard*, are considered as reference points.

OPERATING ENVIRONMENT

While all indications are for future Arctic warming, the region currently remains fully or partially ice-covered for most of the year and will continue to be a harsh environment in the decades to come. The operating locations and seasons in which the GAPV will be capable and likely to operate include year-round in the North Atlantic, Labrador Sea, Bering Sea and Bering Strait, and seasonal summer operations in the North Slope and Northwest Passage.

FIGURE 2 Projected 2030 Operational Areas and Distance to Port

These locations are shown in FIGURE 2, with squares indicating year-round operable locations and circles indicating summer operable locations. Environmental conditions in these areas lead to unique design requirements which have not yet been incorporated into a USN ship. TABLE 1 gives the most extreme conditions which the GAPV is expected to endure.

TABLE 1 GAPV Extreme Operating Conditions

Condition	Extreme Level
Air Temperature	-40 ° C
Ice Coverage	First year Pack
Ice Thickness	Up to 1 m
Sea State (SS)	Transit – SS6; Survivable – SS8
Icing	Severe: > 20 % of the time, > 0.3”/hr
Precipitation	Snow, Hail, Sleet
Lighting	Long Periods of Night or Day
Ceiling	Fog

Key GAPV requirements include the ability to maneuver safely in ice-covered waters, persistently monitor the global maritime domain, respond to disasters or personnel in distress, deter and defend against threats and survey the Arctic environment during self-sustained extended deployments.

The GAPV will meet International Association of Classification Societies (IACS) Polar Class 5 requirements and operate in medium first year ice up to one meter thick which may contain old ice inclusions. It will possess limited ice capabilities while retaining enhanced maneuverability for its own mobility. For access to areas of ice coverage beyond the Polar Class 5 level, the GAPV will operate in conjunction with a more robust icebreaking vessel.

Given that the Arctic ecosystem is both fragile and integral to the global environment; all reasonable and available means to reduce the GAPVs environmental impact will be utilized. Special emphasis will be placed on the potential for integration of emerging environmental technologies into the GAPV design.

DESIGN CAPABILITIES

Expected 2030 environmental conditions and USN Arctic strategy were used to define the necessary GAPV operational capabilities. These include ability to maneuver safely in ice-covered waters, persistently monitor the global maritime domain, respond to disasters or personnel in distress, deter and defend against threats and survey the Arctic environment during self-sustained extended deployments.

DESIGN REQUIREMENTS

The GAPV is required to operate in remote areas and must be self-sustaining for mission durations of up to 120 days and 12,000 nm in open water, allowing for continuous Arctic presence during the summer months. This range will be sufficient for transit between operational areas and ports shown in FIGURE 2 and increased fuel consumption during ice operations. Maximum sustained speed will be at least 17 kt with a goal of 20 kt. Because ice and high sea states will largely limit the GAPV's ability to operate at a maximum speed however, this is a secondary consideration.

TABLE 2 Concept Design Summary

LWL	95.6 m
Beam on WL	18.0 m
Draft	6.25 m
Height	12.0 m
Lightship Weight	5,300 mt
Full Load Weight	6,400 mt
Trial Speed	17.5 kt
Sustained Speed	16.5 kt
Cruise Speed	12 kt
Installed Propulsion Power	15,020 kW
Range	12,000 nm @ 12 kt
Channel Ice Cruise Speed	5 kt
Propulsor	2 VI -1600 ABB Azipods
Power System	IPS: 2 x Wärtsilä 9L32, 2 x Wärtsilä 6L32, 10 SOFCs
Accommodations	146
Initial Operating Capability	Year: 2030
Core Combat Systems	*AAW*: SeaRAM *ASUW*: MK3 57mm gun *C4ISR*: Enhanced suite
Modular Combat Systems	*AAW*: Thales IM 400 mast – SEAMASTER 400 3D Radar, SEAWATCHER 100 2D Radar, non-rot. IFF, Integrated Communications Antennae System *ASW:* UUVs, towed array
Air Complement	2 x MH-60R Helicopters 3 x MQ-8B Fire Scout VTUAVs
Small Craft Complement	Flexible space for hovercraft, airboats, USVs and RHIBs

The projected threat environment for the GAPV is limited to small-caliber arms fire, ramming and small boat attack. The GAPV is to have a small gun armament for combating such threats, and some anti-missile capability for self-defense.

C4ISR systems should be sufficient to transmit real-time information to/from other USN vessels and command, provide at-sea situational awareness and support maritime surface surveillance operations but will only be considered in terms of weight, volume and power requirements. Hanger and support is to be provided for up to two organic MH-60 helicopters and three MQ-8B Fire Scout Vertical Takeoff Unmanned Aerial Vehicles (VTUAV). Aircraft launch and recovery operations shall persist through SS3. Flexible capability for a variety of organic craft, both manned and unmanned is to be included. The GAPV will be designed for initial operational capability in 2030. TABLE 2 summarizes the GAPV concept design.

HULLFORM

The GAPV hullform, shown in FIGURE 3, is designed for combined seakeeping and ice-breaking aptitude. The hull lines are derived from the *KV-Svalbard* and Canadian AOPS concept through which the hull's dual capability has been proven in high sea states and ice-covered waters. A low L/B of 5.4 negatively impacts the GAPV's open-water resistance, limiting its maximum speed but delivering benefits in arrangeable volume, sea-keeping and ice-breaking capability.

FIGURE 3 GAPV hullform underbody

MISSION SYSTEMS

Current USN radar systems are largely not capable of operating in the extreme air temperature conditions for which the GAPV is designed. An enclosed, modular mast as shown in FIGURE 4 protects this equipment from the elements and expedites sensor updates throughout the ship's service life

FIGURE 4 Thales Group IM 400

A 57 mm MK3 naval gun and mounts for .50 caliber machine guns will provide close in weapon support for the GAPV. Missile defense will be accomplished with the RIM-116 Rolling Airframe Missile (RAM). De-icing means and access are important considerations for these exterior weapon mounts.

Sonobuoys will be carried for environmental survey and submarine surveillance; however they are limited in their capability to penetrate steep thermoclines in the Arctic. A towed-array is capable of penetrating thermoclines, but deployment of this apparatus is made difficult by ship maneuvering restrictions while transiting, deploying and recovering the array in ice laden waters.

A robust organic air capability on the GAPV is essential to meet mission requirements. The MH-60 is a multi-mission helicopter selected for its flexibility and adaptable capabilities. The primary functions of the MH-60 will be domain awareness/surveillance, vertical onboard delivery and SAR/MEDEVAC. The MH-60R variant may

be embarked to enhance the GAPV's anti-surface (ASUW) and anti-submarine (ASW) capability.

The Fire Scout VTUAV expands the GAPV envelope of awareness while requiring less crew, fuel and space than a MH-60. The Fire Scout will perform surveillance and intelligence related reconnaissance and contribute to maritime security, safety and protection of natural resources. The combination of up to three Fire Scouts and two MH-60s, as shown in FIGURE 5, will provide a significant projection of force and a tool for awareness in the Arctic.

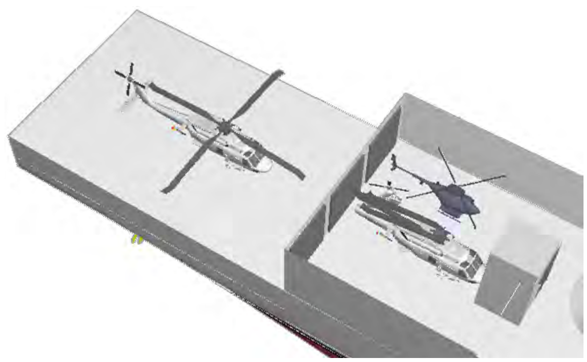

FIGURE 5 Topside Aviation Arrangement

Though it is a critical part of the GAPV's mission capability, air operations will be limited by environmental conditions. Launch and recovery operations are limited to SS3 and below due to ship motions. The MH-60 has both anti-ice and de-icing systems, permitting light-ice operations and temperatures as low as $-40^{\circ}C$. (HAC/SAC 2008) However, Fire Scouts may be negatively affected by temperatures less than $-20^{\circ}C$ in terms of the safety of operations, ground equipment and payload operations. Cloud cover and low ceilings in the Arctic may also affect air operations, while low temperatures and icing are hazards to crew on the flight deck. Therefore adequate protection for operators and watchstanders is an important consideration.

The USN does not currently possess an off-board vehicle capability in the Arctic, nor does it have an operational vehicle specifically designed for Arctic use. To meet maritime security, SAR and environmental survey missions such a vehicle is deemed necessary. The GAPV will be capable of carrying a variety of vehicles in a flexible storage and launch area in order to accommodate future designs and needs. These vehicle alternatives include small hovercraft, airboats and Rigid Hull Inflatable Boats (RHIB).

These options were chosen based on the boats ability to maneuver at low speeds and potential for operation on/in pack ice, brash ice, and open water. Consideration was also given to the vehicle's ability to protect passengers from the environment through the use of an enclosed cabin. Alternatively, mission systems and unmanned vehicles may also be stowed in the storage bays. These may include unmanned underwater vehicles (UUV), unmanned surface vehicles (USV) or a towed array intended for underwater surveillance, seabed mapping and environmental survey purposes.

POWER REQUIREMENTS

Analysis of the GAPV hull was performed using the Total Ship Drag (TSD) program within Integrated Hydrodynamic Design Environment (IHDE) software. FIGURE 6 shows the resulting open water brake power curve in light blue at a draft of 6.25 m.

The powering requirement for transit through Polar Class 5 ice conditions was analyzed to ensure that the GAPV will not be beset by the ice and to provide a measure of ice performance in terms of speed and range. The analysis is based on Finnish-Swedish Ice Class Rules for minimum powering requirements. The rules mandate a minimum 5 kt operating speed in channel ice for all classes. Class IA Super, corresponding to IACS Polar Class 5, requires that this speed be met in channel ice consisting of 1 m thick brash ice with a 0.1 m consolidated layer. These formula-

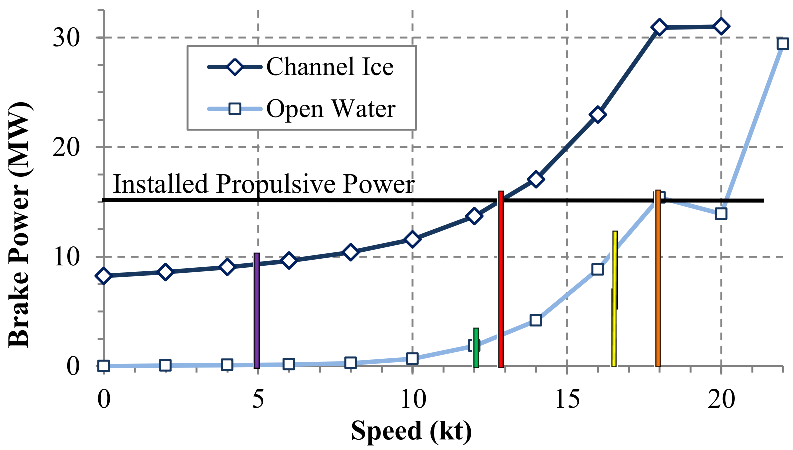

FIGURE 6 Channel Ice vs. Open Water Powering

based rules make the assumption that superposition of ice and open water resistance may be used. (Riska, 2011) Variables for ship geometry, ship size, ice thickness, number of propulsors and propeller diameter are included in the analysis. (Juya and Riska 2011) FIGURE 6 compares the channel ice power requirement in dark blue to that in open water. The GAPV has sufficient installed power (15 MW) to meet the 9 MW required for 5 kt transit through channel ice labeled by the purple line on FIGURE 6 The impact of ice resistance on fuel capacity and range is an important design driver that will be detailed further in the Range section.

ELECTRICAL POWERING

Use of an Integrated Power System (IPS) in the GAPV has several inherent advantages over a mechanical drive. The GAPV is expected to see large variations in propulsion power loads while operating in ice, high sea states or open water. While mechanical prime movers are often inefficient at low or off-prime speeds, managing ship service and propulsion loads on one system lowers variability and allows engines to operate at more efficient levels. Lower fuel consumption and failure rates are also seen as a result.

Survivability is enhanced by enabling the separation of prime movers, power generation equipment and propulsion into multiple electrical zones. Finally, the IPS provides flexibility in power allocation for high heating, de-icing and sensor loads.

The GAPV IPS, shown in FIGURE 7, will consist of four Diesel Generators (DGs) and ten Solid Oxide Fuel Cells (SOFCs). The 15 MW installed propulsion power is sufficient to reach a maximum trial speed of 17.5 kt in open water, shown by the orange line, and 13 kt in channel ice, shown by the red line, on FIGURE 6.

This assumes an ideal system with all systems and DGs operating at maximum level. Realistically from a reliability standpoint a sustained speed of 16.5 kt, labeled in yellow, at 80% of the installed propulsion power is attainable with one Wärtsilä 6L32 DG on standby. At a cruise speed of 12 kt, shown in green, it is feasible to have only one Wärtsilä 6L32 DG online. Without an IPS system, two DG would be required online in a mechanical system at 12 kt resulting in reduced power and efficiency.

Incorporation of fuel cells into a USN ship has yet to be realized, but this emerging technology has potential in its inherent efficiency and low emissions. No moving parts in fuel cells also means that ship vibration, noise and maintenance are all reduced. As a result, GAPV mission duration, range and vulnerability characteristics all stand to benefit from their use. SOFC’s are included in the GAPV design with the assumption that the technology will be matured to a sufficient level for on-board use by 2030. Each SOFC unit must contain its own fuel reformer and be paired with an associated energy storage device, inverter and transformer. The power generated by ten SOFC will cover all base hotel loads so that the more adjustable DGs can focus on variable and propulsion loads.

PROPULSION

Operations in ice-covered waters require a propulsor that will provide enhanced maneuverability as well as the structural capacity to withstand ice impacts. The GAPV will be equipped with two ice-class Azipods such as the ABB Marine VI-1600. The use of podded propulsion on the *KV Svalbard* and USCGC *Mackinaw* has proven this system's capability in operational conditions similar to those anticipated for the GAPV. Yet, unknowns remain in the application of podded propulsion to surface combatants including the reliability of bearings, shock survivability, and long term added maintenance expense. The full GAPV IPS one-line diagram is shown in FIGURE 7.

DE-ICING SYSTEM

The power requirement for topside icing was estimated at over 1 MW. Instead of meeting this load with added power consumption in the IPS, a GAPV waste heat recovery system was conceived which uses SOFC high temperature exhaust gas for shipboard use. Heat exchangers will recoup energy otherwise expelled to the environment, transferring it to a piping system within the deck and superstructure which convectively heats surfaces prone to icing. This also reduces the danger of high temperature exhaust gases to crew and equipment on deck. Given a 250 kW SOFC system with an exhaust temperature of 600˚C, a total of 147 kW of power may be recovered per SOFC for a total effective power recovery of up to 1,470 kW. (Bowman 2011) The impact of added topside weight from such a system was not rigorously considered however.

Two severe icing cases were assessed according to defined conditions. A season condition was categorized by an accumulation rate equal to 0.3 inches per hour, 20 % of the time while a storm condition is this rate 100 % of the time. These conditions assume even, symmetric accumulation over the entire exposed surface of the ship and no wind or sea spray effects. Stability calculations showed that the GAPV could handle 4,000 mt of ice accumulation before capsizing (GM < 0) with no heeling wind or waves present. This ice accumulation assessment is summarized in TABLE 3.

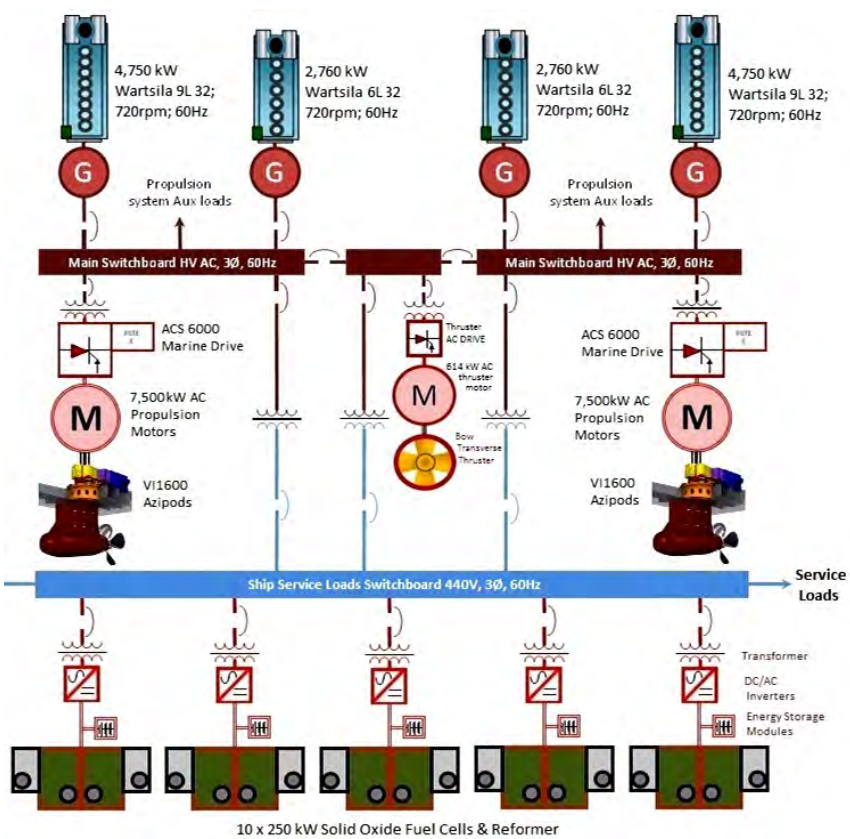

FIGURE 7 IPS one-line diagram

TABLE 3 Icing Survivability Data

	Storm	Season
Accumulation Rate, in./hr	0.3	0.3
% Accumulation Time	100	20
Topside Ice Weight, mt	4,028	4,028
Topside Ice KG, m	14.7	14.7
Ship + Ice Weight, mt	10,429	10,429
Ship + Ice KG, m	8.96	8.96
Survivability Days	8	40

* no heeling wind and minimal sea state

Expectations are that capsizing may occur before GM reaches zero in a given sea-state. However, continuous ice buildup without de-icing through the waste heat recovery system or manual labor is not likely. This study illustrates the potentially severe consequences of de-icing neglect or incapacity.

RANGE REQUIREMENTS

Arctic operations require the GAPV to meet a high endurance range requirement to transit from port to operation areas, and remain in theatre for extended periods without replenishment. FIGURE 2 gives the maritime route distances from potential GAPV operating areas to nearest refueling and repair facilities. Maneuvering in ice-covered waters will also increase fuel consumption and reduce GAPV effective range. While there are Canadian plans to construct a forward naval refueling and berthing port in the Arctic, the timeframe of operability and potential for USN use of such a facility is unknown. (Canwest News Service 2007) The fuel requirement is thus driven by the distance from port of seasonal operating areas and the increased fuel consumption related to ice conditions.

TABLE 4 Seasonal Range Breakdown (nm)

	Fall/Spring	*Summer*	*Winter*
Open Water	6,800	11,000	1,330
Channel Ice	650	120	1,330
Total Range	7,450	11,120	2,660

TABLE 4 is a rational engineering estimate to quantify seasonal conditions in terms of distances traveled at cruise speeds in channel ice at 5 kt and open water at 12 kt throughout a 120 day mission in each season.

The fall/spring and winter ranges are sufficient for transit to and from the Bering Strait or Labrador Sea operating areas with mission capability in theatre. The summer seasonal range permits transit through Canadian Internal Waters in the Northwest Passage, potentially connecting both coasts.

ARRANGEMENTS

The overarching concept for the GAPV general arrangements is utilization of a large internal volume for protection of crew and equipment from unfavorable environmental conditions. All spaces of operation are within internal heated spaces except for the exposed flight deck. Vehicle storage spaces are entirely enclosed with operable doors on both the port, and starboard sides of the ship. An overhead crane within the watertight storage bays will permit launch and recovery of a variety of vehicle options ranging from 11 m RHIB to small hovercraft and UUV. A drying room/ cold weather gear storage and diving rooms are located near the boat space access points. The profile view in FIGURE 8 shows some of the key general arrangement features for the GAPV.

Accommodations for 91 enlisted and 18 CPO are provided within the hull, with 14 officers plus CO and XO in the deckhouse. Dry and cold weather gear (CW) storage areas are appropriately sized for crew sustainment during 120 day mission durations. Berthing is arranged for up to 21 additional detachment personnel including scientific, law enforcement, liaison officers and other parties which may contribute to U.S. Arctic initiatives. A scientific/ flexible mission area is incorporated near detachment accommodations which may be used for environment and climate

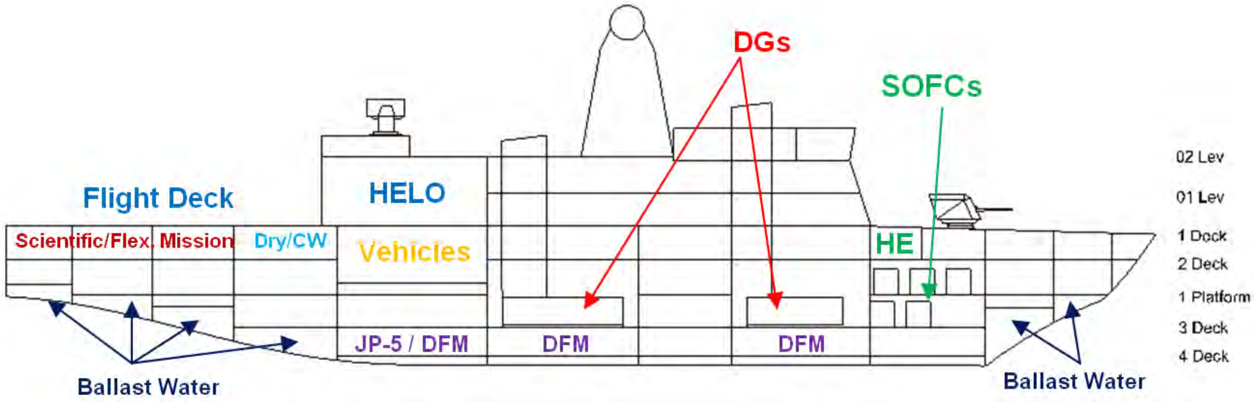

FIGURE 8 General Arrangements

study in the Arctic or other mission related purposes. SOFCs are located near the bow with a large intake/ exhaust trunk to meet consumption demands and ready access for repair/replacement. An enclosed and isolated location for the SOFCs is important for shutoff capability in the case of hydrogen or carbon monoxide leaks.

TANKAGE AND SUBDIVISION

International Maritime Organization (IMO) guidelines give criteria regarding tankage requirements for Arctic operation which may be generalized as follows. (IMO 2002)

- No pollutant may be carried directly against the outer shell without a double skin, and a polar class ship must have a double bottom over its waterline length.
- All polar class ships with icebreaking bow forms and short forepeaks may dispense with double bottoms up to the forepeak bulkhead in the area of the inclined stem, provided that the watertight compartments between the forepeak bulkhead and the bulkhead at the junction between the stern and the keel are not used to carry pollutants.

Adherence to these requirements reduces arrangeable volume in the GAPV and leaves many spaces empty or designated for salt water ballast where typical surface combatants are able to carry fuel and other pollutants. Despite this volume loss, the GAPV must accommodate over 1,000 mt of fuel and oil to meet range requirements.

The GAPV tankage is designed to meet these requirements. A double hull is provided through the entire hull on the wetted surface. Diesel (DFM) and JP-5 fuel are located in deep tanks on 4 Deck above the double bottom in the mid-body. Salt water ballast tanks are located forward and aft in the double hull. Double hull width is 0.8 m; while the double bottom height is on average 1.2 m (minimum of 1 m).

WEIGHTS

Two preliminary weight analyses were performed for the GAPV, using a scaling method and parametric equation coupled with itemized weight method.

The scaled weight breakdown to three Ship Work Breakdown Structure (SWBS) digits was performed using linear and polynomial regression from *Polar Star*, DDG 51, FFG 7 and USCG WMEC weight data. Scaling particulars such as LOA, range or manning were specified based on their relationship to the SWBS weight in question.

The parametric / itemized list method took as its baseline a weight breakdown to two SWBS digits using design data sheet type parametric equations. As design decisions were made and certain

systems defined, their associated weight replaced the previously estimated value. A 17.8 % margin was added to bare hull structural weight based on IACS Polar Class 5 hull strengthening requirements for the ice-belt and bow sections. TABLE 5 shows the scaled and parametric/ itemized SWBS weight breakdown for comparison. The significant weight differences between the GAPV and a USN surface combatant of comparable size include: high structural weight for ice-class requirements, a more efficient though higher weight diesel and SOFC IPS system, and added fuel weight for extended range.

TABLE 5 **SWBS 1-Digit Weight Comparison**

SWBS Group	Itemized (mt)	Scaled (mt)
100	2100	2460
200	1330	971
300	292	273
400	154	161
500	534	673
600	301	352
700	50	56
800	1160	965
Lightship	5240	5440
Full Ship	6400	6410

STABILITY AND SEAKEEPING

DDS079-1 Topside Icing criteria was the GZ criteria used for icing and is representative of the maximum level to which ice buildup will be allowed before manual corrective action is required in addition to de-icing system capabilities. Full load and min op GZ curves in this condition were sufficient for stability though icing did cause a severe drop in GM.

As a limited ice-breaking capable vessel, the GAPV should maintain sufficient positive stability when riding up on ice for crushing/ breaking purposes. (IMO 2002) To assess static ship stability when riding up onto the ice, the ship was assumed to remain momentarily poised at the lowest stem extremity. FIGURE 9 shows a model of the GAPV in such a condition.

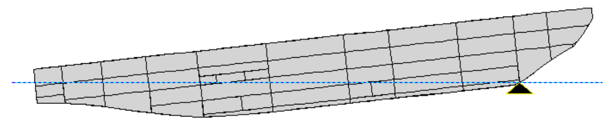

FIGURE 9 **Full Load Ice-Riding Condition**

In this condition, the GAPV was unstable when experiencing topside icing. Careful ballasting in the stern was found to alleviate this issue. Nonetheless, this demonstrates that GAPV performance in sea states and ice flows while encountering topside icing is an issue which would require further investigation.

A CFD seakeeping analysis of the AOPS design completed by STX Canada shows that retractable active fin stabilizers are a necessary feature. Adequate performance of the AOPS was seen in transit, fueling and boat launch/ recovery in SS 6, boarding in SS 5 and helicopter operations in SS 3. (Vyselaar 2011) These results are expected to be indicative of GAPV performance. Use of the vehicle storage bay is likely to occur only in SS2 or less because of its proximity to the waterline.

"GREEN" TECHNOLOGY

Additional green technologies include the use of IMO Tier II diesel engines, a solid and liquid waste management system, a chemical-free ballast water treatment system, and non-toxic coatings. In anticipation of Tier III emission requirements set by the IMO for 2016, complying engines will need to be installed as they become available or exhaust filters will need to be added to the currently designated Tier II certified DGs.

CONCLUSION

Environmental changes associated with global warming, and developing political and economic initiatives in the Arctic region have brought a renewed interest in maritime operations in the far north. The USN currently does not possess a surface combatant capable of operation in the Arctic environment though these developments may lead to the future need for a strategic presence in the area. The 2011 GAPV project developed a USN concept vessel capable of providing a dedicated independent capability to undertake patrol, support diplomatic initiatives and project a US military presence in this region.

The GAPV represents a balanced, feasible concept design that takes into account and accommodates for harsh Arctic environmental conditions as well as the multi-mission requirements anticipated for a USN Arctic patrol vessel. Significant effort has been made through the project to detail the impacts Arctic environmental conditions and required missions will have on ship design practices.

RECOMMENDATIONS FOR FUTURE WORK

As a concept design, the GAPV is simply an idea which lacks refinement in every aspect. In particular, several design considerations were identified which would require special attention. These include:

- Vehicle storage bay feasibility and positioning
- Environmental effects on C4ISR equipment and combat systems
- De-icing/waste heat recovery system feasibility
- Shipboard integration of fuel cells
- Seakeeping and stability during ice operations

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